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Optimisation of Dallenbach Layers using Real Materials

P. Saville

Defence R&D Canada – Atlantic

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January 2007

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Abstract

In this paper multilayer Dallenbach absorbers were designed using the genetic algorithm optimisation routine and known material properties. The genetic algorithm was used to provide the global minimum solution to the reflectivity performance of the absorbers. The bandwidth and reflectivity of the absorber designs depend on the number of layers, layer composition and the layer order. Successful absorber designs are those that present an impedance gradient to the electromagnetic radiation. With the limited number of materials used in this study it was possible to design an absorber with good reflectivity and bandwidth, however, the performance was not as good as found for Jaumann absorbers. Better performance may be achievable for a wider range of materials.

Résumé

Le présent article porte sur les absorbants Dallenbach multicouches mis au point en utilisant la routine d’optimisation de l’algorithme génétique et des propriétés connues des matériaux. L’algorithme génétique a été utilisé pour fournir la solution minimale globale au rendement de réflectivité des absorbants. La largeur de bande et la réflectivité des diverses configurations d’absorbants est fonction du nombre, de la composition et de l’ordre des couches. Les configurations d’absorbants réussies sont celles qui présentent un gradient d’impédance en fonction du rayonnement électromagnétique. Il a été possible de concevoir, avec le nombre limité de matériaux utilisés dans cette étude, un absorbant présentant une réflectivité et une largeur de bande intéressantes; toutefois, le rendement de ce dernier n’était pas aussi bon que celui des absorbants Jaumann. Un plus grand nombre de matériaux permettrait d’obtenir une meilleure performance.

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Executive Summary

Optimisation of Dallenbach Layers using Real Materials:

Saville, P.; DRDC Atlantic TM 2007-012; Defence R&D Canada – Atlantic; January 2007.

Introduction or background: Microwave absorbing materials are categorised by the principle mechanism by which they reduce reflections. Impedance matching absorbers present a graded interface (either dimensional as in a pyramidal absorber, or in material properties) to the incident radiation, while resonant absorbers use destructive interference of waves reflected from different layers in the absorber to minimise reflectivity. Resonant absorbers tend to be more practical for military applications due to the thickness and delicacy of the pyramidal absorbers. Resonant absorbers are further classified as Jaumann or Dallenbach layers. Jaumann absorbers are stacks of resistive sheets separated by low density spacers while Dallenbach layers are homogeneous slabs applied to the reflective surface. In either case absorber design requires optimisation as the reflectivity is a nonlinear equation that cannot be analytically solved for several layers. In this work the optimisation of Dallenbach layers is studied using the genetic algorithm and the properties of several known materials.

Results: Absorber performance was shown to be dependent on the number of layers in the absorber, the layer properties and the order in which the layers were organised. Absorber designs presenting a graded impedance profile to the incident radiation resulted in the best performance. Absorber designs were also optimized as a function of incident angle. Similarities between Jaumann and Dallenbach absorbers are apparent.

Significance: The software and knowledge gained from this study gives us the capability to design optimal Dallenbach absorbers based on available material properties.

Future plans: A wider range of materials with different permittivity and permeability will be investigated to increase the performance and reduce the size for absorbers.

Sommaire

Optimisation of Dallenbach Layers using Real Materials:

Saville, P.; DRDC Atlantic TM 2007-012; R & D pour la défense Canada – Atlantique; Janvier 2007.

Introduction ou contexte: Les matériaux qui absorbent des microondes sont classés suivant leur mécanisme de réduction des réflexions. Les absorbants d'adaptation d'impédance présentent une interface graduelle (dimensionnelle comme dans un absorbant pyramidal, ou comme pour les propriétés des matériaux) au rayonnement incident, tandis que les absorbants résonants utilisent l'interférence destructive des ondes réfléchies par différentes couches de l'absorbant pour réduire au minimum la réflectivité. En raison de l'épaisseur et de la fragilité des absorbants pyramidaux, les absorbants résonants sont généralement plus pratiques pour des applications militaires. Les absorbants résonants sont classés comme des couches de Jaumann ou de Dallenbach. Les absorbants de Jaumann consistent en des empilements de feuilles résistives séparées par des espaceurs de faible densité, tandis que les couches de Dallenbach sont des plaques homogènes appliquées à la surface réflective. Dans ces deux cas, la configuration de l'absorbant doit être optimisée, la réflectivité étant une équation non linéaire qui ne peut être résolue analytiquement pour plusieurs couches. Dans ces travaux, nous étudions l'optimisation des couches de Dallenbach au moyen de l'algorithme génétique et des propriétés de plusieurs matériaux connus.

Résultats: Il a été montré que le rendement des absorbants était fonction du nombre de couches présentes dans l'absorbants, des propriétés des couches et de l'ordre dans lequel ces couches étaient organisées. Les meilleurs résultats ont été obtenus avec la configuration d'absorbants présentant une impédance graduelle au rayonnement incidente. Les similitudes entre les absorbants de Jaumann et de Dallenbach sont apparentes.

Importance: Grâce au logiciel et aux connaissances acquises dans cette étude, nous sommes en mesure de concevoir des absorbants de Dallenbach fondés sur les propriétés de matériaux disponibles.

Perspectives: Un plus large éventail de matériaux, présentant différentes propriétés de permittivité et de perméabilité, seront examinés en vue d'accroître le rendement et de réduire la taille des absorbants.

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1 Genetic Algorithm Optimisation of Multilayer Dallenbach Absorbers

A Dallenbach absorber,[1] is a homogeneous absorbing layer placed on a conducting plane (Figure 1). It is classified as a resonance absorber in that it is designed to be a quarter wavelength in thickness so that electromagnetic waves reflected from the first and second interfaces of the absorber are 180 degrees out of phase resulting in destructive interference. The electromagnetic wave is also absorbed as it passes through the layer and impedance matching is used to reduce the reflection from the air/absorber interface. This last point is usually achieved with multiple absorbing layers that present an impedance gradient from air to the substrate conductor and has the added bonus of increasing the bandwidth of the absorber.

In designing a Dallenbach absorber each layer's thickness, permittivity and permeability can be adjusted in order to optimise the impedance gradient, and improve the resonance effects so that low reflectivity and large bandwidth are achieved. A general solution for the reflectivity of a single layer absorber has been given[2] and design curves have been presented.[3] However, for more than one layer the reflectivity is nonlinear and cannot be analytically solved so optimisation techniques are required in order to obtain good designs. Optimisation of Dallenbach layers has shown that it is not possible to obtain a broadband absorber with only one layer, [4] however several layers stacked together showed increased bandwidth.[5] Multilayer Dallenbach devices have been designed using a Lagrangian optimisation method with constrained variable[6] and a modified Powell method has been used to optimise reflectivity as a function of incident angle and frequency.[7] A stochastic global optimisation technique called the genetic algorithm has been applied, with good results, for designing multilayer Jaumann absorbers.[8-13] The Jaumann absorber is comprised of alternating layers of low density spacers and resistive sheets and provides width bandwidth absorption through resonance effects.

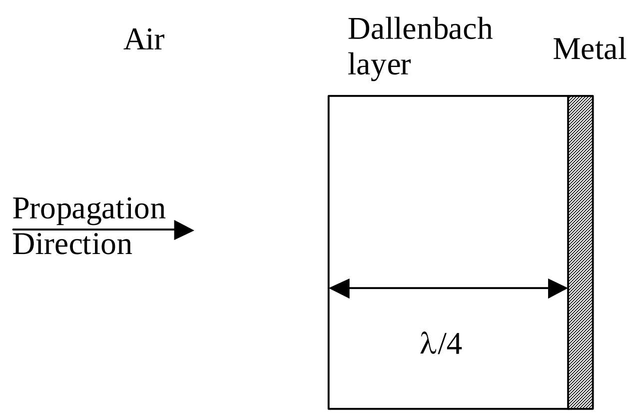

Figure 1: Dallenbach Layer.

The Genetic Algorithm is a stochastic global optimisation routine loosely based on Darwin's theory of evolution and genetics.[14-16] An evolutionary process arrives at the optimized solution over several iterations (generations), by selecting only the best (the fittest) solutions and allowing these to survive and form the basis for calculating the next round of solutions. In this manner the optimisation routine evolves the initial solutions into the optimum.

In this paper, the main focus is to look at the design of Dallenbach absorbers using the genetic algorithm. The intent is to use the properties of existing materials in the design rather than exploring absorber performance based on hypothetical materials. Multilayer designs are considered showing bandwidth increase for absorbers where impedance gradients have been established. Absorber performance as a function of the angle of incidence is also considered and Dallenbach designs compared to Jaumann absorbers.

2 Theory for Calculating the Reflectivity from a Multilayer Absorber

For electromagnetic radiation incident on an interface (Figure 2), some of the radiation is reflected and some is transmitted. The angle of incidence is equal to the angle of reflection and Snell's law of refraction relates the incident and transmitted angles in the two media with refractive indices *n* and *n'*.

$$n \sin\theta_i = n' \sin\theta_t \qquad (1)$$

The fresnel reflection coefficient, ρ, depends on the polarisation of the electromagnetic radiation with respect to the interface, except at normal incidence. An electromagnetic wave interacting with an interface can be considered in terms of its transverse electric and transverse magnetic components.

$$\rho_T = \frac{n_T - n'_T}{n_T + n'_T} \qquad (2)$$

where

$$n_T = \begin{cases} \dfrac{n}{\cos\theta_i}, TMpolarisation \\ n\cos\theta_i, TEpolarisation \end{cases} \qquad (3)$$

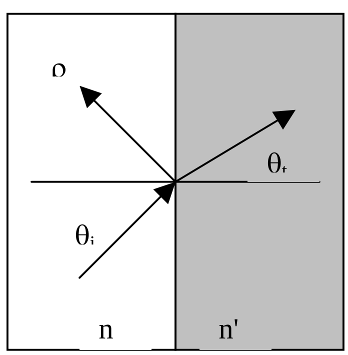

Figure 2: Reflection/Transmission at an Interface.

The characteristic impedance of a medium, η, is related to the refractive index by

$$n = \frac{\eta_o}{\eta} \tag{4}$$

where η_o is the characteristic impedance of free space. Equation 4 can be used to express equations 2 and 3 in terms of the characteristic impedance.

$$\rho_T = \frac{\eta_T' - \eta_T}{\eta_T' + \eta_T} \tag{5}$$

and

$$\eta_T = \begin{cases} \dfrac{\eta}{\cos\theta_i}, TE polarisation \\ \eta\cos\theta_i, TM polarisation \end{cases} \tag{6}$$

Equation 5 can be recast in terms of wavenumbers, *k*, where $\cos\theta = k_z / k$ and $\sin\theta = k_x / k$. First use is made of the relationships $k\eta = \omega\mu$ and $k/\eta = \omega\varepsilon$ to rewrite the TE and TM impedances of equation 6,

$$\eta_{TE} = \frac{\eta}{\cos\theta_i} = \frac{\eta k}{k_z} = \frac{\omega\mu}{k_z}, \quad \eta_{TM} = \eta\cos\theta_i = \frac{\eta k_z}{k} = \frac{k_z}{\omega\varepsilon} \tag{7}$$

The fresnel reflectivity from an interface as a function of polarisation then becomes

$$\rho_{TE} = \frac{\eta_{TE}' - \eta_{TE}}{\eta_{TE}' + \eta_{TE}} = \frac{\mu' k_z - \mu k_z'}{\mu' k_z + \mu k_z'}, \quad \rho_{TM} = \frac{\eta_{TM}' - \eta_{TM}}{\eta_{TM}' + \eta_{TM}} = \frac{k_z'\varepsilon - k_z\varepsilon'}{k_z'\varepsilon + k_z\varepsilon'} \tag{8}$$

If the incident radiation passes through more than a single interface, then the reflectivity coefficient, Γ, to the left of the first interface will include contributions from the reflectivity at every interface in the structure, Figure 2. Knowing the permittivity and permeability for each absorber layer, and the incident angle, the fresnel reflection coefficients can be calculated for each interface using Equation 8. This requires calculation of the wavenumber in the *z*-direction, k_z, for each layer i

$$k_{z\,i} = k_i\cos\theta_i = \omega\sqrt{\varepsilon_i\mu_i}\cos\theta_i \tag{9}$$

where $\omega = 2\pi f$, is the angular frequency and the angle refers to the incident angle in medium i. This angle can be calculated using the identity $1 = \sin^2\theta + \cos^2\theta$, and Snell's law of reflection, Equation 9. Also using $n = \sqrt{\varepsilon\mu}$, k_{zi} becomes

$$k_{zi} = k_i \cos\theta_i = \omega\sqrt{\varepsilon_i\mu_i}\cos\theta_i = \omega\sqrt{n_i^2 - n_a^2 \sin^2\theta_a} \qquad \text{for } i = 1,2,\ldots\text{M,air} \tag{10}$$

where the subscript *a* refers to the air medium. The total reflection coefficient, Γ, to the left of an interface is then given by the expression

$$\Gamma_{Ti} = \frac{\rho_{Ti} + \Gamma_{T,i-1}e^{-2j\delta_{i-1}}}{1+\rho_{Ti}\Gamma_{T,i-1}e^{-2j\delta_{i-1}}}, \text{ for i = 2, 3, …, M+1} \tag{11}$$

where the phase thickness of a layer *i* is $\delta_i = k_{zi}d_i$, and the actual layer thickness is d_i. To summarize, the reflectivity coefficient to the left of an absorber is calculated using Equation 11. First, the permittivity and permeability (or refractive indices) for each layer are obtained. The *z*-direction wavenumber is calculated using Equation 10, and the transverse electric and magnetic components of the fresnel reflectivity for each interface is calculated using Equation 8. The total reflectivity coefficient for each layer is calculated from Equation 11, starting at the left of the rightmost interface, where $\rho_{T1} = \Gamma_{T1} = -1$. For each successive layer Equation 11 is applied until the total reflectivity coefficient is obtained to the left of the air-absorber interface.

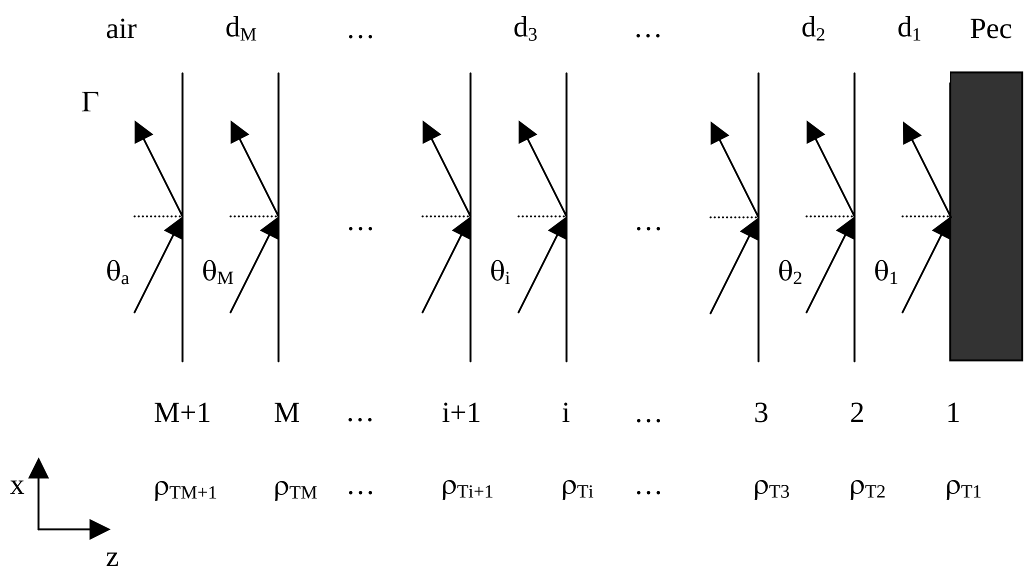

Figure 3: Reflectivity from a multilayer absorber.

The reflectivity of the absorber is calculated by

$$R_T = \left|\Gamma_T\right|^2 \tag{12}$$

and the reflectivity in decibels by

$$R_T\,dB = 10\log R_T \tag{13}$$

3 Experimental

The absorbers studied in this work consisted of slabs (Dallenbach layers) of dielectric-magnetic materials and a perfect electrical conductor, PEC, for backing. Symbolically the absorber design is shown below, with M referring to material M and the subscript N referring to the N^{th} layer.

PEC / M_1 / M_2…. / M_N / air

The absorber population used for optimisation was randomly created by selecting the 10 GHz permittivity and permeability of 3 real materials from a database and a layer thickness in a range between 0.0001 and 0.01 meters.

A bandwidth objective function given by Equation 15 was used to optimise absorber designs at oblique angles of incidence. The fractional bandwidth is defined in terms of the frequency range over which the reflectivity is below the critical reflectivity (-10 or –20 dB), and is calculated by Equation 14, where the denominator is the central frequency of the range under study.

$$BW = 2\left(\frac{f_u - f_l}{f_u + f_l}\right) \tag{14}$$

The bandwidth for perpendicular and parallel polarisations are used to define the objective function used to optimize the absorber structure. This objective function selects for absorber designs where the bandwidths of the two polarisations are equal at the critical reflectivity.[9]

$$OF_{BW} = \frac{BW_{\perp} BW_{II}}{\left(\left|BW_{\perp} - BW_{II}\right| + 1\right)} \tag{15}$$

It was found that the genetic algorithm was better able to converge on an optimized design if a reflectivity objective function was also used. The reflectivity objective function worked on an envelope of the maximum reflectivity from all polarisations and angles of incidence considered. The function was weighted for different frequency regions as

$$OF_{\mathrm{Re}\,flectivity} = w_1 \sum_{i=1}^{N} (R_c - R(f_i)) + w_2 \sum_{i=N+1}^{N+X} (R_c - R(f_i)) + w_3 \sum_{i=N+X+1}^{F} (R_c - R(f_i)) \tag{16}$$

where w_1, w_2, w_3 are weights between 1 and 2 for the different frequency bands, $R(f_i)$ is the reflectivity at frequency i and R_c is the critical reflectivity.

A final objective function (Equation 17) is based on the thickness of the absorber. It is used to help the software probe a wider range of solution space than it might by merely considering the reflectivity or bandwidth.

$$OF_{Thickness} = \frac{1}{\sum_{i} d_i} \tag{17}$$

The three objective functions (Equations 15-17) were experimented with in order to determine which combination of functions where the most informative. The software is designed to produce optimal designs across the solution space resulting in a Pareto Optimal front, beyond which no better absorber designs are to be found for the system under optimisation. For example, convergence using thickness and reflectivity objective functions, results is a curve of design solutions spread across a range of absorber thickness. For any design on the curve or surface, there will be no thinner absorber with lower reflectivity. It was found that using all three objective functions, viewing the 3-D results, and separating the material combinations, provided the best understanding of the solution space, especially when the results at different parts of the solution space are compared via the absorber's reflectivity as a function of frequency.

For the genetic algorithm typically a population of 200 absorbers were optimised for 50 generations with a tournament using 2 participants. The cut-off reflectivity was set at –10 dB and incident angles were run from 0-60 degrees. Although absorbers could be designed with reflectivity below -20 dB, the materials used in this study did not provide wide bandwidths.

4 Results and Discussion

For L layers and M materials it is possible to arrange the materials in M^L combinations. A single layer made from three possible materials has only 3 combinations and the absorber thickness and the optimum reflectivity is easily calculated (Figure 4). Two of the materials (M_1 and M_3) did not produce a reflectivity below -10 dB and so the bandwidth is zero. M_2 did produce reflectivity below -10 dB: its performance oscillates as the absorber thickness increases. In order to understand this behaviour, consider Figure 5, where the reflectivity of M_2 is plotted as a function of frequency and absorber thickness. Several effects are observed in this figure: a null in the reflectivity shifts to lower frequency with increasing absorber thickness, the null decreases in width as it shifts to lower frequency and multiple nodes appear with increasing thickness. The initial increase in bandwidth is a result of the first null walking into the frequency range; peaking when the null is fully in the range. Bandwidth subsequently decreases due to the narrowing of the null, only increasing again as subsequent nulls enter the frequency range. Equation 18 defines the absorber thickness that results in a null based on wavelength and material properties. The minima occur when the absorber thickness is equal to an odd multiple, n, of a quarter wavelength of the electromagnetic radiation in the absorber. The square root term of the permittivity and permeability is the refractive index which accounts for the optical length in the material.

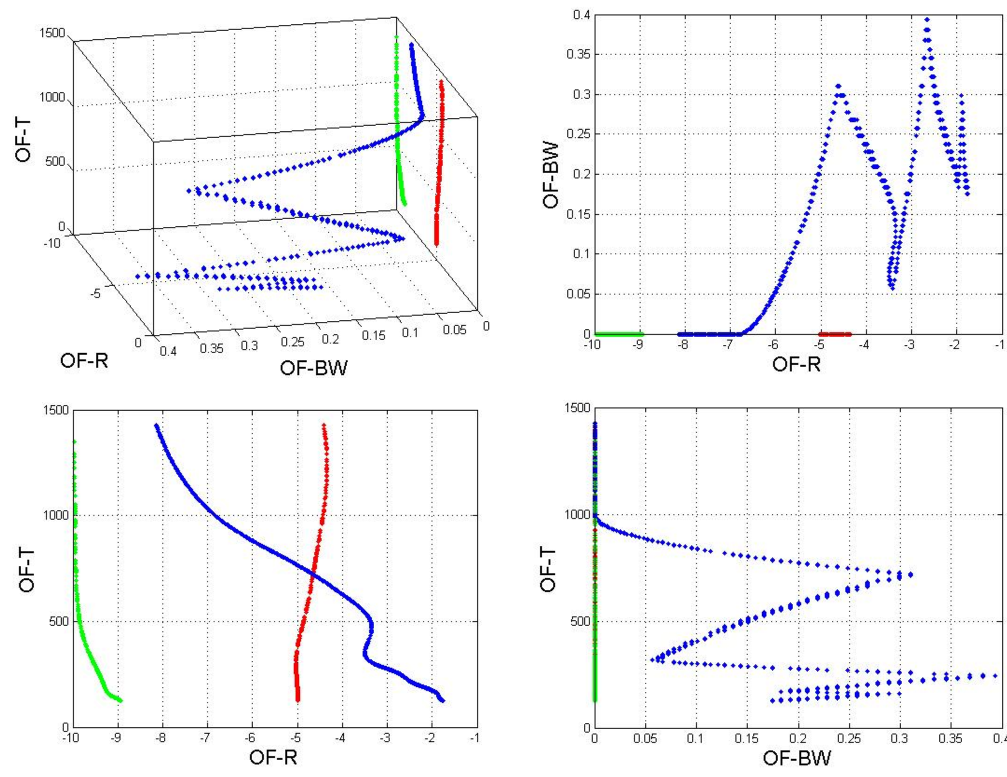

Figure 4: Plots of the objective functions for single layer Dallenbach absorbers made from materials 1 (green) 2 (blue) and 3 (red).

$$d = \frac{n\lambda}{4\sqrt{\varepsilon\mu}} \quad \textit{for } n = 1, 3, 5 \ldots. \tag{18}$$

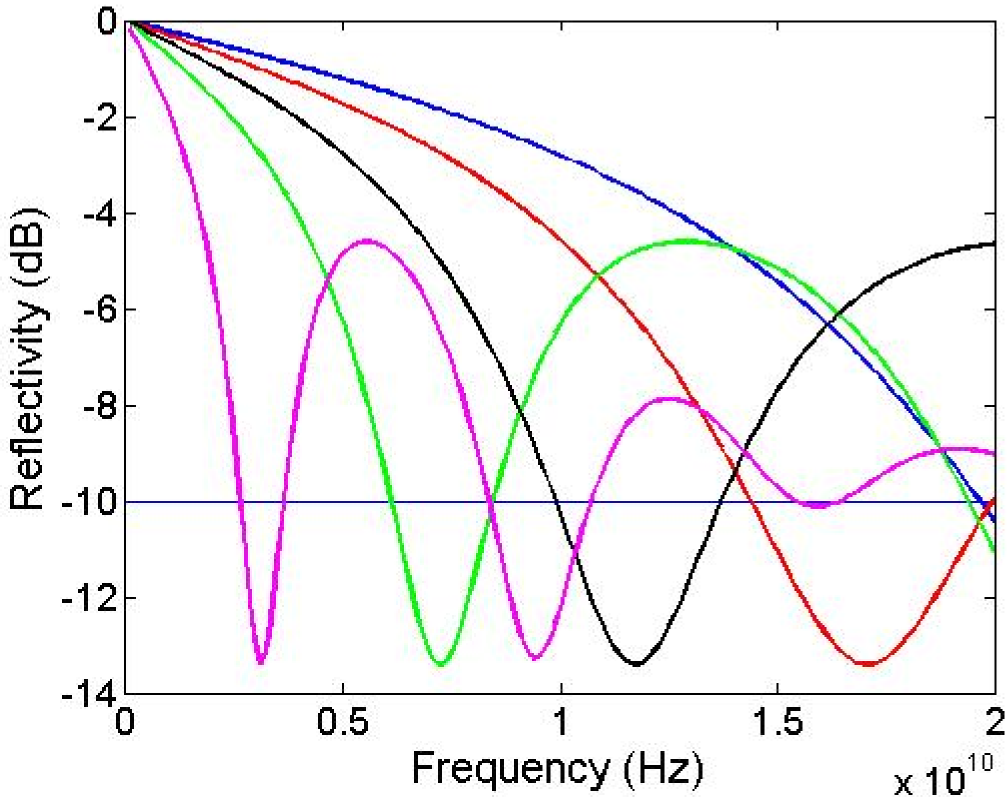

Figure 5: Calculated reflectivity profiles of a single layer Dallenbach absorber as a function of absorber thickness. Blue (1 mm), red (1.4 mm), black (2 mm), green (3.3mm) and pink (7.6 mm).

4.1 Two Layer Dallenbach Absorbers

It is possible to obtain wider bandwidth and lower reflectivity than shown in Figure 5 by optimising the material properties. The objective of this study however, is to determine the best possible absorber that can be formulated using the properties of existing materials. Another way of improving absorber performance is to place one or more impedance matching layers between the absorbing layer and air. Figure 6 presents the bandwidth and reflectivity of several two layer absorber designs with two nulls that have greatly improved performance over the single layer absorbers (Figure 5). More nulls and hence bandwidth can be achieved at the cost of using thick layers, as was seen in Figure 5 and Equation 18.

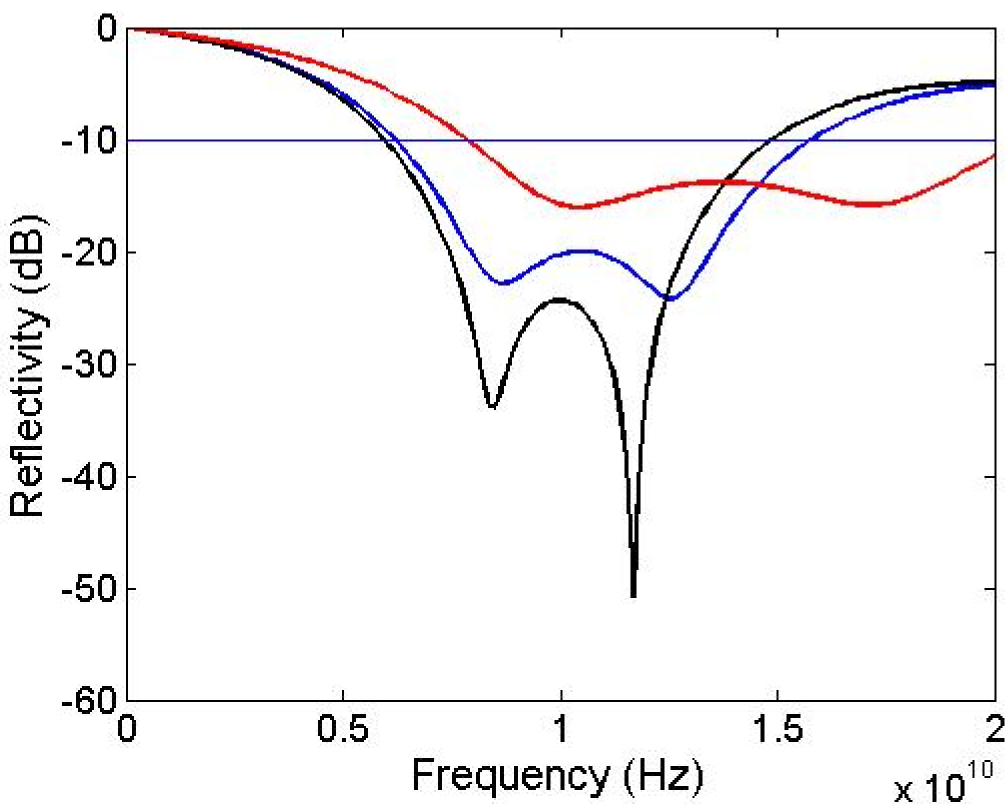

Figure 6: Reflectivity profiles of two layer Dallenbach absorbers constructed in the form PEC/M3/M1/Air. The range in bandwidth and reflectivity is a result of different layer thickness: Total Thickness red 4mm, blue 5.5 mm and black 5.9 mm.

Plots of the objective functions for all absorber designs found during optimisation of two layer absorbers (Figure 7a), show that there are many more possible absorber designs. The red marks in Figure 7a indicate the resulting population after 20 generations of optimisation. In order to understand what these results represent, subsequent plots (7b-d) of the final generation are colour coded to reveal performance as a function of material type. Of the $M^L = 3^2$ possible material combinations, three result in homogeneous absorbers made completely of material 1, 2 or 3. The performances of the single material absorbers are visible as lines of black dots (Figure 7a), similar to those seen in Figure 4 for the single layer absorbers. Only four material combinations survived to the final generation; three of which provide graded impedance profiles. The results presented in Figure 7 represent the non-dominated absorber designs or the Pareto front, which are those designs for which there is no thinner absorber with better reflectivity or bandwidth. As a consequence of this the trajectories for various material combinations appear to be truncated when the performance of another set of materials dominates.

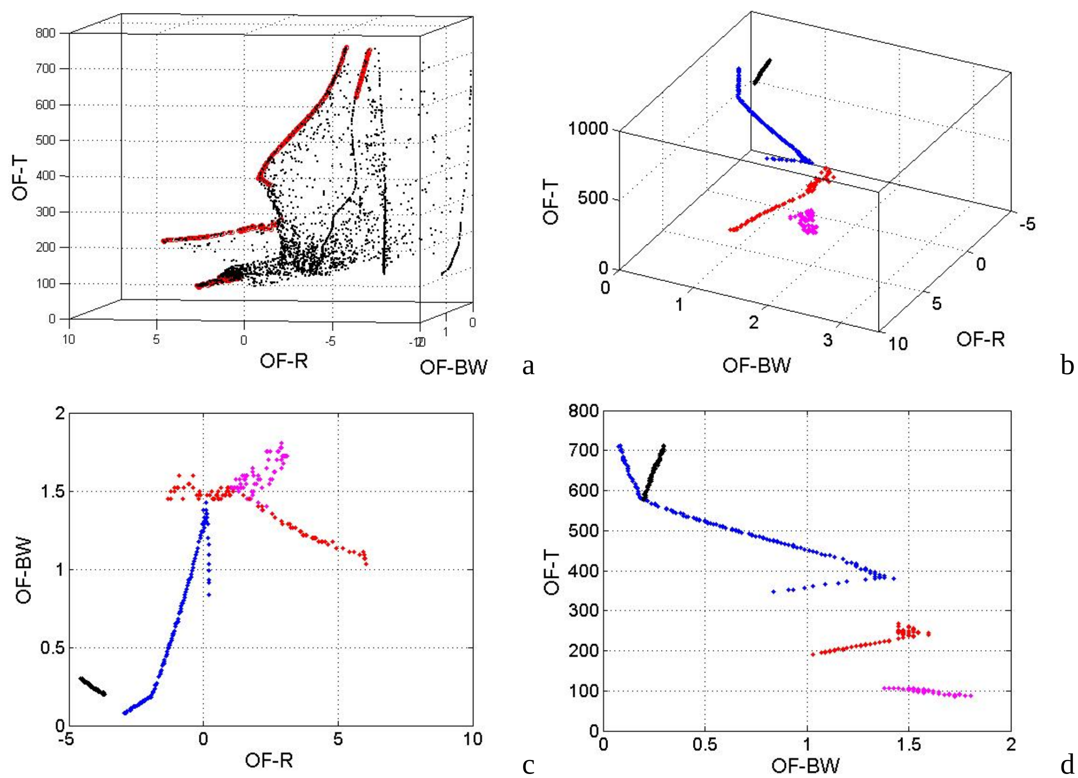

Figure 7: a) Absorber performance plotted as a function of the objective functions for two layer absorbers. Red dots indicate the state of the final optimized generation. b-d) Final optimized generation as a function of material types: black PEC/M_2/M_2/air, blue PEC/M_3/M_2/air, red PEC/M_3/M_1/air and pink PEC/M_2/M_1/air.

4.2 Three Layer Dallenbach Absorbers

Further improvement in absorber performance is obtained by adding another impedance matching layer into the optimisation, Figure 8. The reflectivity profiles of the absorber designs, plotted in this figure, have three nulls and as a consequence a wide bandwidth. The position of the nulls is dependent on the thickness of the layers allowing for absorbers to be designed with the nulls at specific frequency ranges.

For this absorber class there are $M^L = 3^3$ material combinations which when coupled to a wide range of layer thickness results in a large solution space, Figure 9a. This is evident in the broader scatter of data. Only four material compositions result in optimised designs (Figures 9b-d), and of those, two are really two layer absorbers (*PEC/*M_3*/*M_1*/*M_1*/air* and *PEC/*M_3*/*M_2*/*M_2*/air*). The set *PEC/*M_3*/*M_2*/*M_1*/air* produces the widest bandwidth (red dots in Figure 9d) and not surprising represents a graded impedance profile.

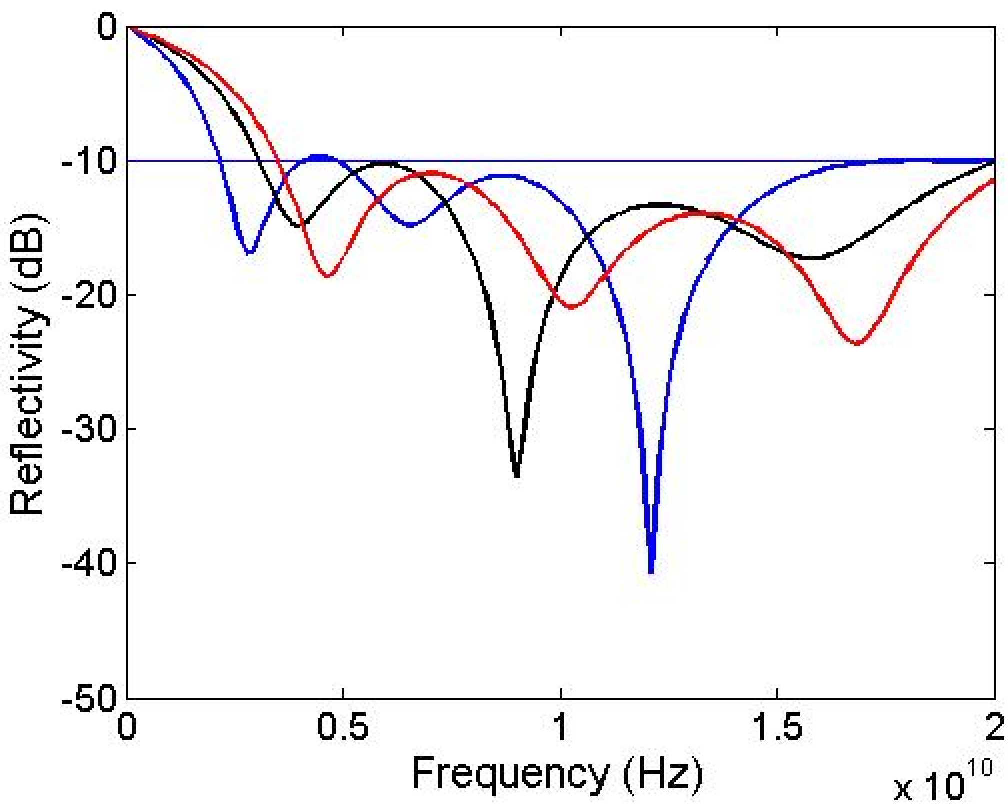

Figure 8: Performance of several three layer designs using PEC/M_3*/*M_2*/*M_1*/air that result in three nulls and have a bandwidth below -10 dB.*

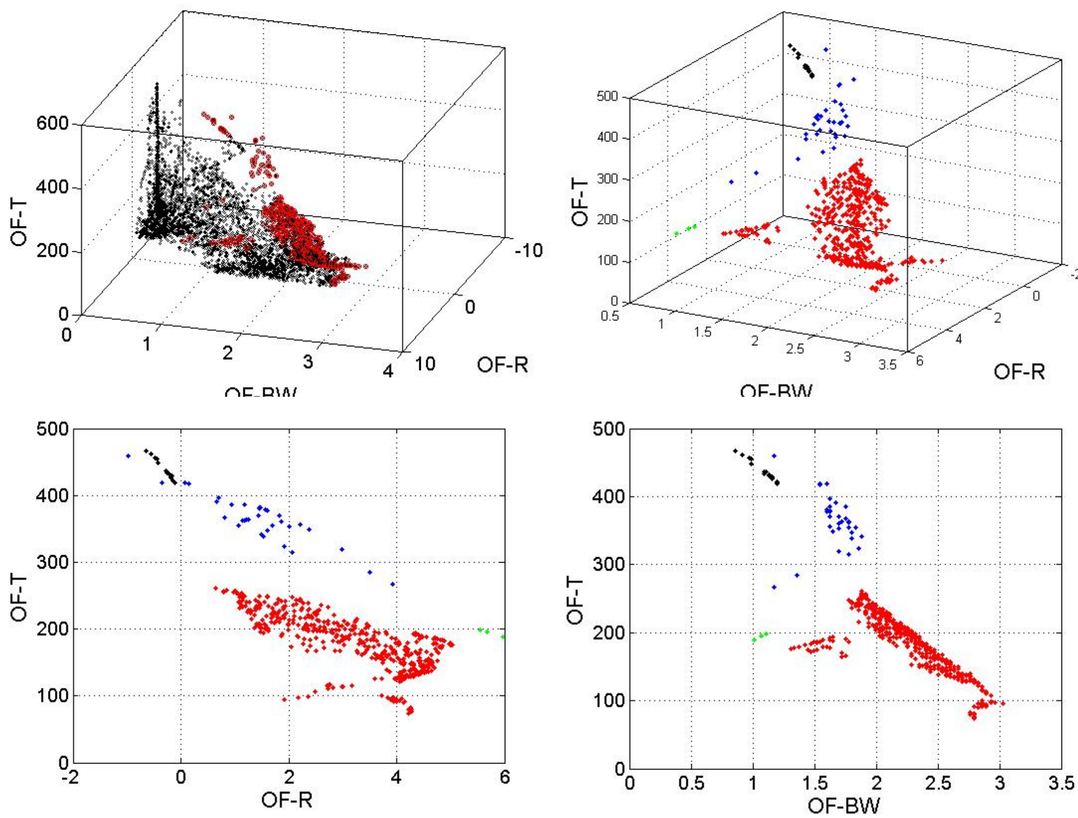

Figure 9: Performance plots for three layer Dallenbach absorbers.

4.3 Absorbers with Four or More Layers

Subsequent layers do improve the performance of the absorbers, though as a consequence of the limited number of materials used in this study, the improvement is typically due to an increase in layer thickness. The dominant design follows the impedance profile established for the three layer absorber; $PEC/M_3/M_2/M_1/air$, with one of the layers thicker, such as $PEC/M_3/M_2/M_1/M_1/air$. An alternate form found is $PEC/M_{1\ or\ 2}/M_3/M_2/M_1/air$ which was observed for Jaumann absorbers with high permittivity spacers. Having more materials available that will allow a smooth impedance gradient to be created will improve the performance of the absorber, though with diminishing returns in bandwidth. The three layer absorber designs already cover about 70% of the bandwidth at -10 dB. A practical use for more layers or thicker absorbers would be to increase the bandwidth at lower reflectivity (eg R = -20 dB).

4.4 Optimisation as a Function of Incident Angle

So far in this discussion only normal angles of incidence have been considered. Absorber performance can also be optimised over a range of incidence angles and polarisations, Figure 10. Optimisation is performed by calculating the reflectivity at a range of incident angles and polarisations and then evaluating the envelope of the reflectivity curves with the objective functions. As with an earlier study of Jaumann absorbers[17], designs optimized at normal incidence performed well up to an angle of incidence of about 30 degrees, after which performance decreased. Conversely absorbers optimized at high angles of incidence performed well to low angles however, at a smaller bandwidth. It was also found that performance was better for absorbers composed of more layers.

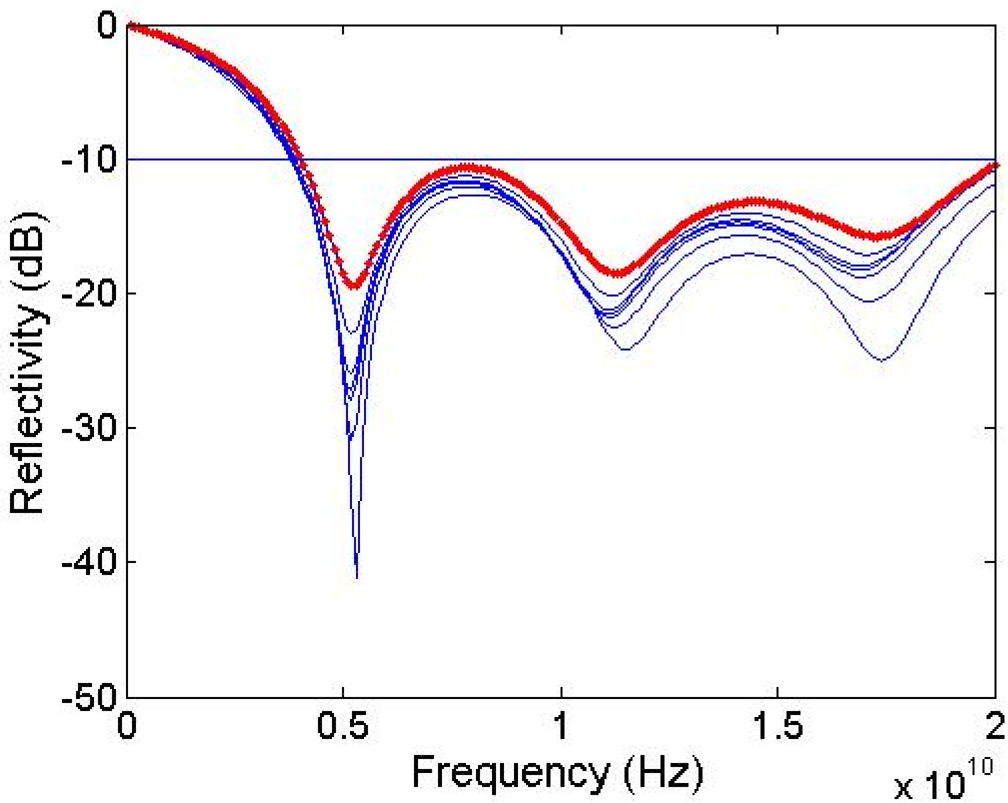

Figure 10: Reflectivity of an optimized 3 layer absorber for angles of incidence 0, 10, 20 and 30 degrees and two polarisations (blue lines). The overall reflectivity envelope is given by the red line.

5 Conclusions

The genetic algorithm provides a method of optimising Dallenbach absorber designs using the properties of available materials. In the optimisation, objective functions for the bandwidth, reflectivity and absorber thickness were used. Convergence of the routine resulted in a Pareto front, or absorber designs where no thinner absorbers will be found with better reflectivity and bandwidth. Optimal absorber designs tend to include a graded impedance profile.

Based on this limited study of materials, it appears that Dallenbach absorbers do not perform as well as Jaumann layers due to a poor impedance match between air and absorber. It is expected that with a wider range of materials, including conductors and magnetic materials, would enhanced performance. Dallenbach absorbers tend to be more robust because of the materials and design.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
PEC	Perfect Electrical Conductor
R&D	Research & Development

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In this paper multilayer Dallenbach absorbers were designed using the genetic algorithm optimisation routine and known material properties. The genetic algorithm was used to provide the global minimum solution to the reflectivity performance of the absorbers. The bandwidth and reflectivity of the absorber designs depend on the number of layers, layer composition and the layer order. Successful absorber designs are those that present an impedance gradient to the electromagnetic radiation. With the limited number of materials used in this study it was possible to design an absorber with good reflectivity and bandwidth, however, the performance was not as good as found for Jaumann absorbers. Better performance may be achievable for a wider range of materials.

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Genetic Algorithm, Optimisation, Absorber Design, Dallenbach, Absorber, Multilayer

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